Smart Machining Systems

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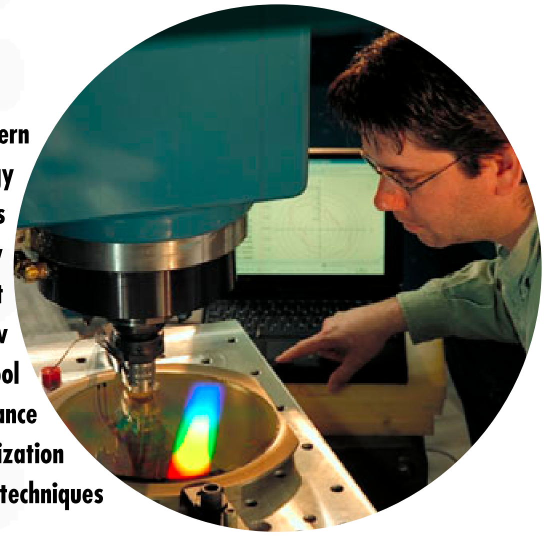
Program Funding:	$2.8 M
FTEs:	9

Program Goal

Develop metrology methods and standards that enable U.S. industry to characterize, monitor, and improve the accuracy, reliability and productivity of machining operations, leading to the realization of autonomous smart machining systems.

Problem

Coalition on Manufacturing Technology Infrastructure (CTMI) identified an urgent need for "enabling dramatic improvements in the productivity and cost of designing,planning, producing, and delivering high-quality products within short cycle times." CTMI identified thrust areas in process definition and design, smart equipment/process control, fundamental understanding of process and equipment, health monitoring/assurance and integration framework. It also stated that metrology and standards are key enablers of these thrust areas. This program aims to facilitate the development and validation of such measurement methods and standards. A successful program will enable the smart machining systems to cost effective manufacture the first and every part to specification and on schedule.



Modern metrology instruments allow development of new machine tool performance characterization techniques

Approach

The program focuses on developing a methodology for seamlessly integrating all science-based understanding or representation of material removal processes and machining system performance to carry out dynamic and global optimization. There are three programmatic focus areas: (1) performance characterization and representation; (2) process optimization and control; and (3) condition monitoring.

Typical Customers and Collaborators

Boeing, Caterpillar, Pratt& Whitney, Cincinnati Lamb, Hardinge Brothers, Bosch-Rexroth, Ford, Northrop Grumman, Optodyne, Roy-G-Biv, Third Wave Systems, VulcanCraft, American Petroleum Institute, Lion Precision, Heidenhain, Renishaw, Gibbs Associates, IQL, Association for Manufacturing Technology (AMT), The Integrated Manufacturing Technology Initiative (IMTI), U.S. Army, National Nuclear Security Administration (NNSA), National Aeronautics and Space Administration (NASA), University of Massachusetts, University of North Carolina Charlotte, University of Auckland, University of Aachen, University of Maryland.

For more information see page 111

smart machining

Smart Machining Systems

Goal

Develop, validate, and demonstrate the metrology, standards, and infrastructural tools that enable U.S. industry to characterize, monitor, and improve the accuracy, reliability and productivity of machining operations, leading to the realization of autonomous smart machining systems.

Program Manager:
Alkan Donmez

Total FTEs:
9

Annual Program Funds:
$ 2.757 M

Customer Need & Intended Impact

Machining systems are used for discrete part and tooling fabrication and hence are integral to the manufacture of durable goods. Annual U.S. expenses on machining operations total more than $200 billion, about 2% of Gross Domestic Product (GDP). A study conducted by the Association for Manufacturing Technology (AMT) in 2000 indicated that the advancements in machine tools and related manufacturing technologies created benefits worth a total of nearly $1 trillion in the U.S. over the period 1994-1999. These benefits resulted from gains in productivity, declines in inventory requirements, and manufacturing related product improvements for price, quality and energy efficiency.

Over the last two years there has been an intensive effort originated by three NIST/MEL programs, Smart Machine Tools, Predictive Process Engineering and Intelligent Open Architecture Control that have evolved toward a common theme of Smart Machining. These MEL efforts joined with the National Science Foundation (NSF) and Integrated Manufacturing Technology Initiative (IMTI) to organize and conduct a Smart Machine Tool Workshop in December 2002 bringing government, industry and academia together to identify the U.S. needs in technology development in the area of smart machine tools and machining systems. As a result of this workshop, U.S. manufacturing industry represented by Association for Manufacturing Technology (AMT), National Center for Defense Manufacturing and Machining (NCDMM), National Center for Manufacturing Sciences (NCMS), National Coalition for Advanced Manufacturing (NACFAM), National Tooling & Machining Association (NTMA), Society of Manufacturing Engineers (SME), and TechSolve, established the Coalition on Manufacturing Technology Infrastructure (CMTI) in 2003. This coalition produced a technology roadmap for the Smart Machine Platform Initiative (SMPI) in March 2004. The original three MEL programs strongly influenced the structure and content of the SMPI technology roadmap. The Smart Machining Systems (SMS) program continues this evolution and is closely aligned with the SMPI technology plan.

CMTI indicates in its 2004 Technology Plan that productivity and quality gains achieved by the U.S. manufacturing industry over the last decade are challenged by low-wage countries. As a result, outsourcing of manufacturing in economically critical industries such as automotive, aerospace, consumer products, and heavy equipment is increasing. On the other hand, advanced technologies and engineering innovations are bred in advanced manufacturing environments facilitated by significant amount of interactions. Losing these manufacturing environments, the U.S. is in danger of losing its edge in advanced technology and innovations as well.

CMTI identified an urgent need to reverse this trend by "reinvention of the basic manufacturing environment, enabling dramatic improvements in the productivity and cost of designing, planning, producing, and delivering high-quality products within short cycle times." CMTI further identified five primary thrust areas to address the challenges facing the U.S. manufacturing sector that produces metal parts and fabrications:

a. Process definition and design

b. Smart equipment operation and process control

c Fundamental process and equipment understanding

d. Health monitoring and assurance

e. Integration framework

Metrology and standards are identified as key enablers of these thrust areas. The Smart Machining Systems (SMS) program aims to facilitate the development and validation of such measurement and related technologies and standards.

A successful program will enable cost effective manufacture of first and every part to specification and on schedule by the smart machining systems. Such systems will complement and enhance the skills of machine operators, process planners and design engineers in the manufacturing enterprise by sharing the knowledge and information among these functions to optimize the design and manufacturing processes to their fullest. Loaded with high fidelity process and performance models and optimization tools, smart machining systems will behave in a predictable and controllable manner. This will eliminate trial-and-error based prototype development and reduce time to market, and thus advance the capability of U.S. industry to respond to the global pressures of mass customization of high quality products.

An advanced manufacturing environment is conducive to engineering innovations. Reversing the trend of outsourcing to low-wage countries will enable U.S. industry to regain its competitive edge in innovations and productivity. This competitive advantage will minimize the adverse effects of trade imbalances on the U.S. economy.

Technical Approach & Program Objectives

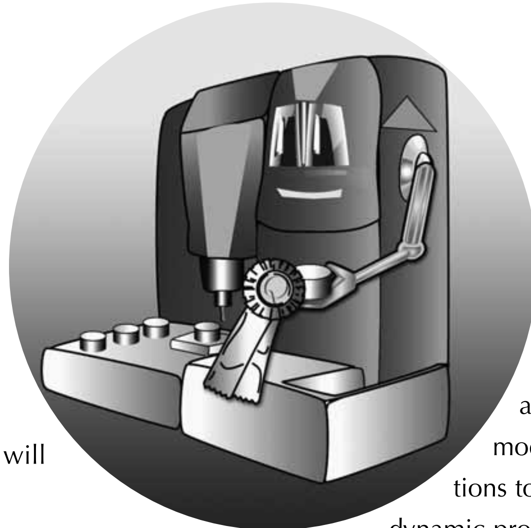
To enable cost effective manufacture of first and every part to specification and on schedule, a smart machining system will have the following characteristics:

- It will know its capabilities/condition and will communicate this information
- It will monitor and optimize its operations autonomously
- It will assess the quality of its work/output
- It will learn and improve itself over time

These characteristics require a science-based understanding and unambiguous representation of material removal processes and machining system performance.

There are three programmatic focus areas:
(1) performance characterization and representation;
(2) process optimization and control; and
(3) condition monitoring.
Development of dynamic and global optimization tools and methodology that will integrate the physical understanding of all system components will be the unifying theme of all these focus areas.

To meet program goals and objectives as well as communicate the applications of developed concepts and tools to stake holders, the program will focus on three types of projects: development of fundamental methods and data; development of demonstration platforms; and high-risk projects with potential paradigm changing outcomes. Demonstration platforms will also serve to promote stronger collaboration with equipment/software vendors leading to better outreach.



Objective #1: Dynamic optimization

Develop a generic methodology and associated data and modeling specifications to carry out dynamic process optimization, based on design requirements, integrating all related process and equipment knowledge and information.

As stated in SMPI Technology Plan, the ability to account for and accurately predict or describe the propagation of errors in a machining platform is vital for estimating and emulating real-world performance, but represents a major gap in the current technology. Although significant information related to performance of machine tools, machining processes, cutting tools, and materials already exist, there is no unified methodology to combine all this information to generate optimum machining conditions with expected outcomes. Furthermore, very little of this information is standardized, making the optimization even more difficult to generalize.

Accomplishing this objective will enable science-based process design and quality control, which are key requirements for smart machining systems.
A generic optimization capability based on well-defined cause and effect relationships will also be an enabler for reasoning and learning capability of smart machining systems.

Objective # 2: Equipment characterization

Develop measurement methods, models and standards to characterize and communicate the machine tool performance under operating conditions.

Information about machine tool performance forms one of the primary foundations necessary to enable manufacturing the first and every part to specifications. Traditionally machine tool performance is determined using a series of tests conducted under quasi-static conditions. There are series of national and international standards describing these tests. These performance parameters are used to buy and sell machines as well as to predict the capability of machine tools for specific family of parts. The differences between the national and international standards cause the vendors and the users of the machines tools great difficulty and confusion about the claimed performance parameters for contractual and capability estimation purposes. Harmonization among these standards is considered a first priority for this objective. Furthermore, the relationships between the quasi-static performance parameters and obtainable part tolerances are not very well defined because under operating conditions the performance of the machine is not the same as for the quasi-static conditions. The AMT roadmap targets an 80% improvement in accuracy of machine tool between 1995 and 2010. Machine tool vendors and users have already exhausted their options to improve the performance based on quasi-static machine behavior. Measuring and modeling of performance under operating conditions are the main enablers left to improve machine performance.

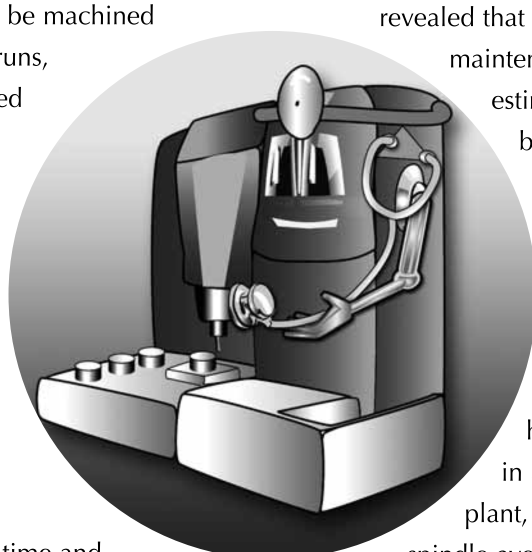
Objective #3: Next generation NC

Develop, implement and demonstrate all necessary STEP-NC compliant interfaces and data specifications for seamless operation of model-based machine control.

Smart machining systems need a rich set of information to fully exploit their capabilities. Current Numerical Control (NC) programs are written in “G codes” which express primitive tool paths. These programs do not include information about as-is or to-be geometry, features, tolerances, material properties, fixture location, material removal rates or other information developed during the design and process planning stages. This information is stripped out when converting to G codes, severely limiting the ability of the controller to optimize machining or react to disturbances. Fine tuning processes to maximize performance with current methods is very expensive, tedious and time consuming, and cost effective only for very large part lots. Mass customization and penetration to small manufacturers remain elusive. STEP-NC, an international standard - ISO 14649 “Data model for computerized Numerical Controllers,” is the enabling standard that provides the potential for using the digital product model as machine tool input. STEP-NC extends STEP (ISO 10303) – the STandard for the Exchange of Product model data into the NC world.

Boeing and Fanuc recently carried out a case study to demonstrate the impact of incorporating more information into NC process. In this study, Fanuc augmented their G code language with codes signifying the tolerances associated with subsequent tool motions. Boeing’s process planners used these G codes to indicate where roughing passes and final finishing passes were taking place. Fanuc's Computerized Numerical Controller (CNC) adjusted its dynamic parameters, such as speed through corners and the amount of blending allowed, and demonstrated a 30% reduction in machining time. This simple example underscores the drastic improvement that can be achieved in smart machining, when proper information is utilized by the controller.

Information/data generated by process and equipment models and effectively utilized by the controller will enable parts to be machined more quickly with fewer dry runs, prototypes and scrap; improved surface finish and material properties such as work hardening and residual stress; and less variation in parts over large lots. These benefits will accrue to large-volume manufacturers, who can achieve a higher percentage of time-in-cut; and also to small-volume manufacturers, who can save time and cost on prove-outs.



Objective #4: Condition monitoring and reliability

Develop and validate measurement, sensing and analysis methods and associated data specifications and metrics to verify that machine and the process are operating within expected design limits.

Unscheduled downtime of manufacturing equipment is one of the most important impediments to achieving cost-effective, timely production schedules. A recent study by the maintenance and Reliability Center of the University of Tennessee revealed that current estimated industrial maintenance expenditure in the U.S. is estimated to be $500 billion to $700 billion. The same study estimated that development and implementation of condition-based and pro-active maintenance technologies could save $100 billion to $200 billion annually. One example for such high cost of maintenance is that in a large aerospace manufacturing plant, typical life for a machine tool spindle averages between 40 and 400 hours of operation and the plant consumes 1000 spindles per year. If one considers the cost of stopping the production and replacing the large spindle unit at this frequency, even without a damaged tool or the workpiece, it is apparent that the cost savings will be enormous with a smart machining system that monitors its own condition.

Several industrial partners are very interested in collaborating with us in the area of condition monitoring of spindles. Timken, producer of spindle bearings, and Ford Motor Company, a major spindle user, are providing equipment to help us to do research in this area. The spindle test stand that Ford is considering loaning to us is a very unique facility to emulate the real life operation of variety of spindle types used in machine tools. With this test stand we will be able to carry out controlled experiments to correlate the deterioration of spindle performance and spindle condition data. The use of such a test stand allows tuning and improvement of algorithms and sensor applications for spindle condition monitoring and condition based maintenance. Such a system will avoid unscheduled downtime and enable cost savings mentioned above

Objective #5: In-situ metrology

Achieve a breakthrough in advanced metrology to enable direct measurement of the pose of the cutting tool or measuring probe relative to workpiece with an uncertainty better than 5 m and 2 arcseconds in a 1 m^3 cubic workzone.

Most accuracy problems in machine tools and Coordinate Measuring Machines (CMMs) are related to indirect measurement of the tool or probe positions with respect to the workpiece. Due to large Abbe offsets introduced by stacked slides configurations of traditional machine tools these indirect measurements cause large uncertainties in the measurements.

Because of these uncertainties and the uncertainties introduced by the machining process, machined parts have to be inspected to verify that they are within the design specifications. Post process inspection is very costly non-value added activity requiring CMMs or other custom designed inspection systems. Eliminating this activity would save significant time, money and other scarce resources such as skilled labor. We know that Boeing and Caterpillar are very interested in implementing independent measurement systems in their machine tools. Although it is a high risk effort, achieving this objective will, at a minimum, enable direct on-machine measurements and certification of machined parts. Furthermore, a successful system would allow for breakthrough improvements in machine accuracy. It dramatically lowers current requirements and costs for accurate slideways, carefully controlled heat sources, a thermally invariant and stiff machine tool structure, and a solid foundation. Finally, such a system will significantly lower the requirements for stable environmental conditions, one of the highest hidden costs to achieving precision.

Major Accomplishments

Calibrating Kolsky Bar Temperature Measurements with Pure Aluminum and Zinc Samples

Performed experiments where pure aluminum and pure zinc samples were melted to aid in the calibration of the pyrometers and thermal imaging cameras used in Kolsky bar apparatus. The melting point experiments provide two known temperatures to record and confirm the calibration of the instruments.

Cutting Temperature and Force Measurements of Aluminum and Titanium Alloys Performed

Measured machining temperatures and forces for orthogonal cutting of titanium (Ti6A14V) and aluminum (AL7075-T651) using dual-spectrum, high-speed video and three-axis force measurement. Preliminary analysis of the results indicates that the lower thermal conductivity of the ceramic tool material appears to have the predicted effect of directing more of the heat from the cutting process into the chips. Comparisons between measurements and model-based predictions indicate generally favorable agreement for cutting forces, with opportunities for improvement in prediction of thrust forces through improved friction modeling.

Development and Deployment of New Optical Configuration of High-Speed Infrared Camera

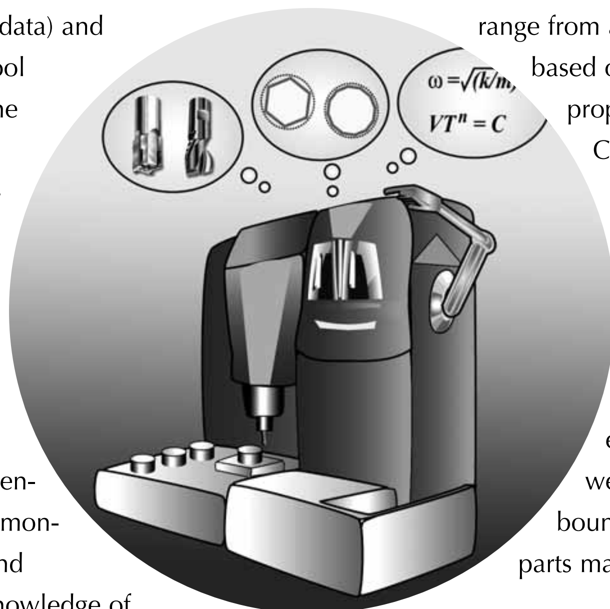
A new optical configuration for the high-speed infrared video camera involving a new reflective lens with a larger depth of field was developed. This new configuration yields a significant improvement in depth of field over the prior configuration, yielding sharper images of target objects with rough surfaces allowing us to image the rough side the chip at the tool-workpiece interface.

National and International Standards for Machine Tool Performance

We continued to provide the Secretariat for ISO/TC39/SC2 "Test Conditions for Machine Tools" and for the American Society of Mechanical Engineers (ASME) B5/TC52 "Performance Evaluation of Machine Tools." Accomplishments include: 1) New revision of ASME B5.54 "Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers;" 2) Contributions for major restructuring, modernization, and harmonization of ISO 230-1 "Geometric Accuracy;" 3) Publication of ISO 230-9 addressing measurement uncertainty of obtained performance parameters; 4) Development and extensive experimental evaluation of test methods and performance parameters for errors due to the heat generated by high-speed axis motions for the revision of ISO 230-3; 5) Conducted tests for evaluation of environmental vibration effects on machine tool structure and provided results for inclusion in ISO/CD 230-8 machine tools test code for determination of vibration values; 6) Experimental study on the application of a laser vibrometer to test error motions of ultra high-speed spindles; 7) Collaborative report to ISO and ASME on test procedures for the alignment of machine axes, with a focus on four- and five-axis machining centers; and 8) Eight ISO Draft International Standards (DIS) and three Committee Draft standards (CD) on machine tool test methods.

Machine Tool Data Standards

We continued to provide the Secretariat for the ASME B5/TC56 Standards Committee "Information Technology for Machine Tools." Accomplishments include: 1) Ballot ready draft standards ASME B5.59-1 (performance test data) and ASME B5.59-2 (machine tool properties); 2) Reports of the activity to ISO TC39 (machine tools) and TC184 (Industrial automation systems and integration) gaining support for an ISO activity; 3) Updated reference schemas, example files, and style sheets, to facilitate implementation, field-testing, and demonstration of the standards; and 4) Demonstration of self-knowledge of the turning center testbed through a description of its properties and performance data according to the information model in B5.59-1 and B5.59-2.



Smart Transducer Standards

We still lead the development of suite of standards associated with smart transducer applications. Accomplishments this year include: 1) The Institute of Electrical and Electronics Engineers (IEEE) 1451.4 standard "Smart Transducer Interface for Mixed-Mode Communication Protocol" was re-balloted and approved as a standard on May 2004. It will be published by IEEE in 2004.; 2) Developed the IEEE 1451.1 neutral model (data and object models) in JAVA and published them in the IEEE 1451 open-source repository.

Prediction of Workpiece Errors

Developed prototype capability to translate machine tool performance parameters into error bounds for the form and dimensional errors of elementary machined features. The developed techniques range from an error-budget approach based on the laws of uncertainty propagation to detailed Monte Carlo simulations, and take into account the effects of uncertainties in machine errors. Measurements were performed on a machining center to assess and model key geometric and thermal error sources. The results were used to predict the error bounds of features on a series of parts machined at different times.

STEP-NC Performance Testing

Developed interpreters for two components of STEP-NC, the underlying data model (ISO 14649) and the STEP-integrated model (ISO 10303 AP-238) to investigate the computational burden for parsing data files in real time. Tests indicated that the performance of the interpreters was comparable, and that no significant penalty executing the STEP-integrated model was incurred.

STEP-NC Conformance Testing

In collaboration with The Boeing Co., test procedures were designed to determine if STEP-NC data for complex curved parts can be executed the same way on NC machine tools from various manufacturers. The data includes materials, cutters and tolerances as well as traditional geometry and features. NIST's 5-axis machining center with a Siemens 840D CNC complements several Boeing machines in both machine configuration and NC control. The tests uncovered numerous discrepancies between machines, and Boeing is implementing short-term workarounds while the underlying problems are being resolved.

STEP-NC Data Visualization Software Written

The software to visualize tool paths resulting from the execution of STEP-NC (ISO 14649) machine tool programs was developed. The new visualizer can be used to draw tool paths for the other supported programming languages, making it more broadly useful.

FY2005 Projects

Robust optimization of machining (Objective #1)

A mathematical framework will be developed to define dynamically adjusted objective and constraint functions for optimizing the whole machining operation taking into account machine performance, process capability, part design specifications, time and cost.

Physics-based modeling of machining (Objective #1)

A dynamic property model (constitutive model) for the material to be used in the optimizer demonstration case for the first project will be developed. The project will continue experimental work in (1) orthogonal machining with force, thermal and visible video measurements of tool and chip interface, and (2) dynamic material property measurements with pulse heated Kolsky bar apparatus.

Machine tool performance characterization and improvement (Objectives #2 and #5)

This project will focus on the following major activities: (1) national and international standards development, (2) development and field testing of standardized information models and associated data formats for machine tools, (3) implementation of Bayesian approach to machine tool performance modeling and quality control, (4) predictive tolerance analysis of machined parts, (5) exploration of advanced metrology enabling machine self calibration, in-situ part inspection, in-situ dynamic tool characterization, and improved feedback on realized pose of the cutting tool.

Next generation NC for smart machining systems (Objective #3)

Data and interface requirements for adaptive control implementations to extend the capabilities of existing NC standards will be identified and documented. There will be two parallel activities: (1) review STEP-NC data model and its support for adaptive control, (2) install Siemens STEP-NC software onto the 5-axis machining center controller to carry out initial testing of its capabilities. Tests will include Roy-G-Biv's Extensible Markup Language (XML) based controller interface, XMC, for model-based control data exchange.

Model-based machine tool control (Objectives #2 and #3)

This project will be the demonstration platform for the development of techniques to improve the efficiency of turning operations at Picatinny Arsenal and its supplier base through the application of open-architecture model-based machine control to both new and existing machine tools.

Smart spindles: Testbed verification (Objective #4)

The requirements for real-time spindle condition monitoring and diagnosis system will be investigated. This will be based on sensing and signal processing scheme, which involves preliminary optimization of sensor placement, under static and dynamic radial loading conditions.

Typical Customers and Collaborators

Industry:

- Alibre
- Alcoa
- AMT
- API
- Boeing
- Bosch-Rexroth
- Caterpillar
- Cincinnati Lamb
- DaimlerChrysler
- EDS PLM
- Esprit
- Ford Motor Company
- General Dynamics
- GE Fanuc
- General Motors
- Gibbs & Assoc
- Hardinge Brothers
- Heidenhain
- IBM
- IMTI
- IQL
- Knowledge Based Systems
- Lion Precision
- Max Spindle
- MIMOSA

- Northrop Grumman
- Okuma
- Optodyne
- Pratt & Whitney
- Renishaw
- Roy-G-Biv
- Siemens
- STEP Tools Inc
- Third Wave Systems
- Unova
- VulcanCraft

Government:

- Army Picatinny Arsenal
- Los Alamos National Labs
- NASA
- Oak Ridge National Labs
- Sandia Labs (potential)

Universities:

- University of Florida
- University of Maryland
- University of North Carolina at Charlotte
- Southern University
- University of Massachusett
- University of Aachen, Germany
- Pohang Institute of Science and Technology, Korea
- University of Loughborough, UK
- University of Auckland, New Zealand FY2005

Standards Participation

- ANSI/ASME B5 Machine Tools (Member)
- ANSI/ASME B5/TC52 Machining & Turning Centers (Secretariat)
- ANSI/ASME B5/TC56 Information Technology for Machine Tools (Chair and Secretariat)
- ANSI/ASME B89.3.4 Axes of Rotation (Observer)
- ISO TC 39 Machine Tools (Member of the US Delegation)
- ISO TC 39/SC2 Test Conditions for Machine Tools (Secretariat)
  - ISO TC 39/SC2/WG1 Geometric Accuracy of machine tools (Member)
  - ISO TC 39/SC2/WG3 Test Conditions for Machining Centers (Member)
  - ISO TC 39/SC2/WG6 Thermal Effects on Machine Tools (Convener)
  - ISO TC39/SC2/WG7 Reliability, capability and availability of machine tools (Member)
  - ISO TC39/SC2/WG8 Vibration of machine tools (Member)
- ISO TC 184/SC 1/WG 7 Data modeling for integration of physical devices (Member)
- ISO TC 184/SC 1/WG 8 Distributed installation in industrial applications (Member)
- ISO TC 184/SC4 Industrial Data (Member of the US Delegation)
- ISO TC 108/SC 5/WG 6 Data Processing and Analysis Procedures for Condition Monitoring and Diagnostics of machines, Including Formats and Methods for Communicating, Presenting and Displaying Relevant Information and Data (seeking active participation)

Smart Machining Systems